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Experience in designing the foundations of a multi-storey building on the eluvial soils of the Urals using a model of non-linear soil deformation

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Abstract. The article describes an example of the first design of the foundation of a high-rise building in the Middle Urals using a non-linear soil model that reflects the real deformation properties of the soil. The use of an effective model that reflects the real deformation properties of the soil has allowed to reduce the cost of the foundation by more than two times while increasing of its reliability.

1. Introduction

Eluvial soils, as initial weathering product of rocks, have high strength properties and low deformability; in the Urals, their capacity can reach significant sizes.

However mistakenly piles in these solid soils are sometimes used, that often turns out to be economically and technically inexpedient solution. Also important is the fact of negative influence of damage of the eluvial hard layer supporting upper soil layers of the construction site which are basis of water-bearing and other networks of existing and newly constructing buildings.

At the same time now-days requirements for geotechnical design primarily due to the multiple increase in the power of personal computers are aimed at consideration of real mechanical properties of soils in designing foundations. These real mechanical properties, based on the physical nature of soils, are realized in their physically and geometrically non-linear character of deformation.

2. Model of non-linear soil deformation

Geometric nonlinearity associated with large displacements in soil massifs is reflected by geometric relationships [1] in equations of the problem. The essence of physical nonlinearity consists in dependence of soil stiffness on its stress state. Thus, initial stiffness characteristics of soil (bulk deformation modulus K and shear modulus G) in contrast to Hooke's theory, change with change in the soil stress state. Phenomenologically, in the framework of continuous medium concept about decomposition of common strain tensor ε_{ij} on volumetric strain ε and shape strain ε_i: $\varepsilon_{ij} = \varepsilon + \varepsilon_i$ and on the corresponding decomposition of stress tensor $\sigma_{ij} = \sigma + \sigma_i$, such deformation in coordinates of invariants of stress and strain tensors looks like that shown in Figure 1, opposed to linear deformation studied by Hooke and characterized by the deformation diagram shown in Figure 2. The diagram in Figure 2 is typical for structural materials (metals, concrete, rubber) and for rock.

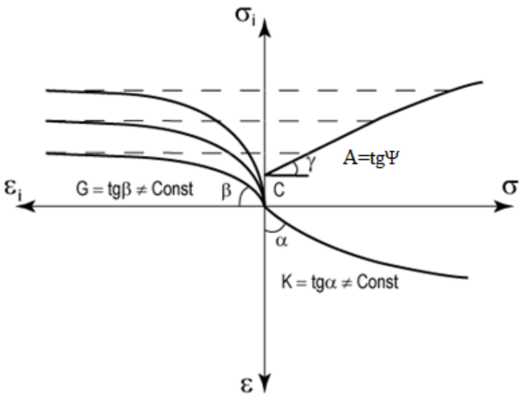

Figure 1. Simplified nonlinear soil deformation diagram

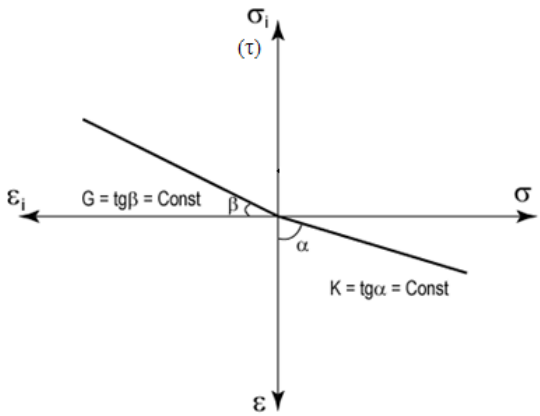

Figure 2. Diagram of linear deformation of structural materials (metals, concrete, plastics, rubber), as well as a rock; notation here is the same as in Figure 1

As follows from the diagram for structural materials and for rock, the basic stiffness characteristics K and G can be considered as stress-independent constants, while for soils; they are functions of stresses. Graphes in Figure 1 can be expressed using formulas (1) [3,4]:

$$K = \frac{\sigma}{\varepsilon} = \frac{\sigma^{1-\alpha}}{A_0}, \qquad G = \frac{\sigma_i}{\varepsilon_i} = \frac{\sigma_U}{B + \varepsilon_i}. \tag{1}$$

Here $\sigma_U = A\sigma + C$ – strength condition of Mises-Botkin for soil; A_0, α, A, B, C – parameters depending on the type of the soil.

As follows from formulas (1), shear stiffness of the soil G is related to its strength, which is absolutely logical, since it is shear stresses in the soil and shear deformations in it that leads to entail soil destruction [5]. According to the theory of continuous media, the main characteristics of soil stiffness (bulk deformation modulus K, shear modulus G, Young's modulus E and Poisson's ratio ν) are related by relations (2) [6]:

$$E = \frac{3KG}{K + G}, \qquad \nu = \frac{K - 2G}{2(K + G)} \tag{2}$$

From relations (1) and (2) it follows, for example, an increase in the deformation modulus E with increasing depth [7, 8], which is not provided for by Hooke's theory with constant modulus E. Thus, a physically nonlinear theory indicates a greater rigidity of the soil base than follows from the physically linear theory of Hooke.

Dependence of parameters A, B, C of the type of stress state $\mu_\sigma = (2\sigma_2-\sigma_1-\sigma_3)/(\sigma_1-\sigma_3)$ reflects also another important mechanical property of soils, namely, dependence of their rigidity on conditions of loading (type, intensity, loading area); here $\sigma_1>\sigma_2>\sigma_3$ – principal stresses. One of the main consequences of this feature of soils is the difference in the results of their static tests by different kinds of methods. However, the main difference between soils and structural materials is natural origin

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of soils over millions of years, during which not only their structure was formed, but also their natural stress state.

Such a history of soil formation cannot be reproduced in laboratory conditions in principle, as a result of which the calculated deformations of soil bases according to laboratory data differ from real values by about two times [8]. Therefore, parameters A_0, α, A, B, C of physically nonlinear soil model must be determined from in-situ tests. For this purpose, only pressuremeter and plate loading test devises (preferably automatic similar to those shown in figures 3, 4, 5) must be used since only these devices allow as much as possible to keep natural state of the soil, provided that they are technologically correct installed in the soil massif and tests are methodically correct carried out, taking into account the features of the physically non-linear soil model used to analyze their results.

Figure 3. Automatic pressuremeter device for in-situ tests in bore holes

Figure 4. Automatic self-boring pressuremeter device for in-situ tests in the massif of weak water-saturated soils (including offshore)

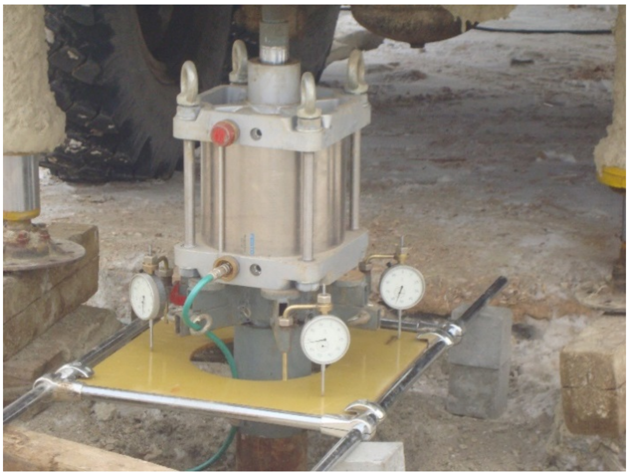

Figure 5. Automatic plate loading test device for in-situ tests in bore holes

In the notation of the diagram: bulk deformation modulus $K = \sigma/\varepsilon$; shear modulus $G = \sigma_i/\varepsilon_i$; σ, ε – first invariants of stress and strain tensors (volumetric deformation); σ_i, ε_i – second invariants of the deviator parts of the tensors of stresses and deformations (shape change – shear).

3. Implementation in the design

Based on the above considerations, it was decided to design for the first time in Yekaterinburg spread slab foundation of multi-storey building using, in accordance with requirements of the Federal Law of Russian Federation №384-FZ ("Regulations on the Safety of Buildings and Structures") [9] an effective physically and geometrically nonlinear soil model. Sectional view of the designed foundation is shown in Figure 6.

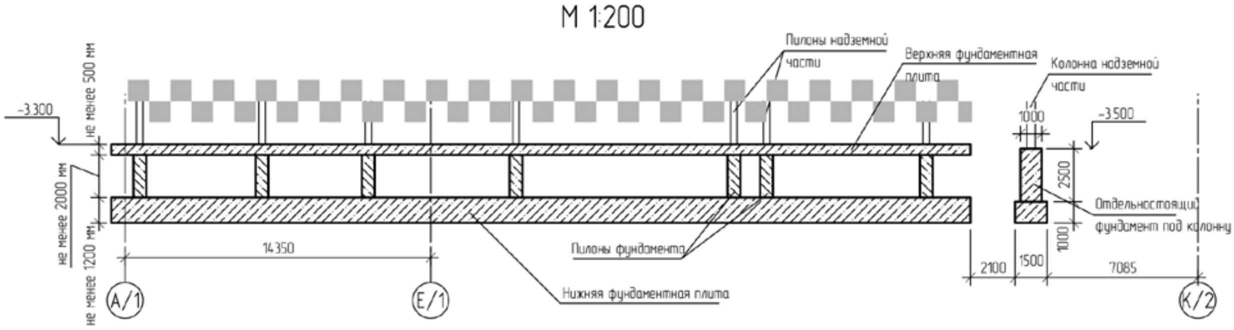

Figure 6. Sectional view of the designed foundation

The box-shaped form of the foundation was adopted off presence of a large thickness of heterogeneous, previously laid for leveling the relief of the site, soils, which had to be constructively overcome in order to transfer the building load to a reliable bearing eluvial soil.

Characteristics of the nonlinear soil model were determined by the method described in [10], main feature of which is special (using minimization methods) processing of the results of in-situ soil tests with solving so-called ill-conditioned problem [11], with regularizing its solution taking into account geotechnical properties of soils, including preliminary approximate values of some parameters of nonlinear soil model according to the results of an auxiliary laboratory mechanical soil tests. To determine the final values of the parameters of nonlinear deformation of soils corresponding to their natural state, data from pressuremeter (see Figure 7) and plate loading test see Figure 8) were used.

Figure 7. Pressuremeter test

Figure 8. Plate loading test

During construction of the building, geodetic observations of its deformations were carried out, which showed good agreement with calculated data based on the physically nonlinear soil model and, on the contrary, serious, similar to those specified in [6], deviations from results of Hooke's linear model. Foundation, designed taking into account the nonlinear properties of soils was almost two times cheaper than the foundation designed on the basis of outdated methods of Hooke's linear theory: cost of the building of the foundation, taking into account of nonlinear properties of the soils was $ 0.7 million (48 million rubles), while on the base of linear theory there was $ 1.3 million (85 million rubles).

During the construction of the building, geodetic observations of its settlements were carried out, which showed good agreement with the calculated data based on the physically nonlinear soil model and, on the contrary, serious, similar to those specified in [6], deviations from the results obtained using Hooke model (linear deformation).

Figure 9. Excavation for the box foundation in eluvial soil

Figure 10. Bottom plate of the box-shaped foundation

Figure 11. Construction of first eight floors of the building

4. Conclusion

Foundations and underground structures should be designed based on non-linear theory of soils. In this case, it is possible to design and build most reliable and cheap their constructions.

Parameters of nonlinear soil model must be determined from in-situ test data.

The use of an effective model that reflects the real deformation properties of soil had allowed to reduce the cost of the foundation by more than two times while increasing its reliability.

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